NON-PROVISIONAL PATENT APPLICATION

CROSS REFERENCE TO RELATED APPLICATIONS

This application is a divisional application of co-pending application Serial Number 10/072,587, filed February 8, 2002 and claims the benefit of U.S. Provisional Application number 60/267,306 filed on February 8, 2001. The subject matters of the prior applications are incorporated in their entirety herein by reference thereto.

FEDERALLY SPONSORED RESEARCH OR DEVELOPMENT

This invention was made with government support under Contract No. N00024-01-C-4034 awarded by the United States Navy.

TITLE

Current Control Device

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to a current control device for regulating current flow. The invention specifically described is a device wherein current flow is regulated by compression and expansion of a composite.

2. Related Arts

Mechanical circuit breakers are best described as a switch wherein a contact alters the electrical impedance between a source and a load. Mechanical breakers are typically composed of a snap-action bimetal-contact assembly, a mechanical latch/spring assembly, or an expansion wire. Such devices are neither gap-less nor shock resistant, therefore prone to chatter and subject to arcing. Chatter and arcing pose substantial

problems in many high-voltage applications.

Variably conductive composites are applicable to current control devices. Compositions include positive temperature coefficient resistive (PTCR), polymer current limiter (PCL), and piezoresistive formulations. PTCR and PCL applications and compositions and piezoresistive compositions are described in the related arts.

Anthony, United States Patent No. 6,157,528, describes and claims a polymer fuse composed of a PTCR composition exhibiting temperature-dependent resistivity wherein low resistivity results below and high resistivity results above a transition temperature.

PTCR composites are composed of a conductive filler within a polymer matrix and an optional nonconductive filler. Chandler et al., United States Patent No. 5,378,407, describes and claims a PTCR composite having a crystalline polymer matrix, a nickel conductive filler, and a dehydrated metal-oxide nonconductive filler. Sadhir et al., United States Patent No. 5,968,419, describes and claims a PTCR composite having an amorphous polymer matrix, a thermoplastic nonconductive filler, and a conductive filler. During a fault, the composite heats thereby increasing volumetrically until there is sufficient separation between particles composing the conductive filler to interrupt current flow. Thereafter, the composite cools and shrinks restoring conduction. This self-restoring feature limits PTCR compositions to temporary interrupt devices.

PCL composites, like PTCR compositions, are a mixture of a conductive filler and a polymer. However, PCL composites are conductive when compressed and interrupt current flow by polymer decomposition. For example, Duggal et al., United States Patent

No. 5,614,881, describes a composite having a pyrolytic-polymer matrix and an electrically conductive filler. During a fault, temperature within the composite increases causing limited decomposition and evolution of gaseous products. Current flow is interrupted when separation occurs between at least one electrode and conductive polymer. Gap dependent interrupt promotes arcing and arc related transients. Furthermore, static compression of the composites increases time-to-interrupt by damping gap formation. Neither PTCR nor PCL applications provide for the dynamically-tunable compression of a composite in response to electrical load conditions.

Piezoresistive composites, also referred to as pressure conduction composites, exhibit pressure-sensitive resistivity rather than temperature or decomposition dependence. Harden et al., United States Patent No. 4,028,276, describes piezoresistive composites composed of an electrically conductive filler within a polymer matrix with an optional additive. Conductive particles comprising the filler are dispersed and separated within the matrix, as shown in Figures 1A and 1C. Consequently, piezoresistive composites are inherently resistive becoming less resistive and more conductive when compressed. Compression reduces the distance between conductive particles thereby forming a conductive pathway, as shown in Figures 1B and 1D. The composite returns to its resistive state after compressive forces are removed. However, piezoresistive compositions resist compression.

Pressure-based interrupt facilitates a more rapid regulation of current flow as compared to PTCR and PCL systems. Temperature dependent interrupt is slowed by the poor thermal conduction properties of the polymer matrix. Decomposition dependent

interrupt is a two-step process requiring both gas evolution and physical separation between electrode and composite. Furthermore, decomposition limits the life cycle of a composition.

Active materials, including but not limited to piezoelectric, piezoceramic, electrostrictive, magnetostrictive, and shape-memory alloy materials, are ideally suited for the controlled compression of piezoresistive composites thereby achieving rapid and/or precise changes to resistivity. Active materials facilitate rapid movement by mechanically distorting or resonating when energized. High-bandwidth active materials are both sufficiently robust to exert a large mechanical force and sufficiently precise to controllably adjust force magnitude.

As a result, an object of the present invention is to provide a current control device tunably and rapidly compressing a pressure-dependent conductive composite. A further object of the present invention is to provide a device that eliminates arcing thereby facilitating a complete current interrupt. It is an additional object of the present invention to provide a device that quenches transient spikes associated with shut off.

SUMMARY OF THE INVENTION

The present invention is a current control device controlling current flow via the tunable compression of a polymer-based composite in response to electrical load conditions. The invention includes a pressure conduction composite compressed by at least one pressure plate. In several embodiments, the composite is compressed by a conductive pressure plate. In other embodiments, the composite is compressed by a nonconductive pressure plate and current flow occurs between two electrodes contacting

the composite. The composite is variably-resistive and typically composed of a conductive filler, examples including metals, metal-nitrides, metal-carbides, metal-borides, metal-oxides, within a nonconductive matrix, examples including polymers and elastomers. Optional additives typically include oil, preferably silicone-based.

A compression mechanism applies, varies, and removes a compressive force acting on the composite. Compression mechanisms include electrically driven devices comprised of actuators composed of an active material extending and/or contracting when energized. Active materials include piezoelectric, piezoceramic, electrostrictive, magnetostrictive and shape memory alloys. Piezo-controlled pneumatic devices are also appropriate. Actuator movement adjusts the pressure state within the composite thereby altering resistivity within the confined composite.

Several advantages are offered by the present invention. Compression-based control of a pressure-sensitive conduction composite provides a nearly infinite life cycle. A gap-less interrupt eliminates arcing and arc quenching requirements. The present invention lowers fault current thereby avoiding stress related chatter. Parallel arrangements of the present invention offer power handling equal to the sum of the individual units.

BRIEF DESCRIPTION OF THE DRAWINGS

The invention will now be described in more detail, by way of example only, with reference to the accompanying drawings, in which:

FIG. 1 is a schematic diagram showing exemplary microstructures for composites before and after compression.

FIG. 2 is a flowchart of composite manufacturing method.

FIG. 3 is a side elevation view of a pressure switch with conductive pressure plates.

FIG. 4 is a side elevation view of a pressure switch with nonconductive pressure plates.

FIG. 5 is a side elevation view of a current controller comprised of four pressure switches wherein pressure plates are pushed by actuators.

FIG. 6 is a side elevation view of a current controller comprised of four pressure switches wherein pressure plates are pulled by actuators.

FIG. 7 shows a parallel arrangement of current controllers comprising a single unit.

FIG. 8 is a top elevation view of pressure switch showing cylindrical pores oriented through electrodes.

FIG. 9 is a section view of pressure switch showing cylindrical holes through switch thickness.

FIG. 10 is a section view of pressure switch showing cylindrical holes within composite.

FIG. 11 is a section view of pressure switch showing cylindrical holes filled with a temperature sensitive material.

FIG. 12 is a side elevation view of temperature activated switch.

FIG. 13 is a side elevation view of temperature activated switch.

REFERENCE NUMERALS

1 Current controller

2 Conductive filler

3 Nonconductive matrix

4 Composite

6 First electrode

7 Second electrode

11 Pressure switch

18 Pressure plate

19 Actuator

22 Force

30 Restoration element

31 Conductor

32 Insulator

33 Insulator

40 Hole

41 Temperature sensitive material

51 Temperature sensitive actuator

52 Wire

53 Wire

54 Nonconducting terminal

55 Rigid element

56 Thermal element

DESCRIPTION OF THE INVENTION

Two embodiments of the present invention are comprised of a rectangular solid composite 4 contacting and sandwiched between two or more plates, namely a planar first electrode 6 and a planar second electrode 7, as shown in FIG. 3, and a planar first electrode 6 and a planar second electrode 7 and two planar pressure plates 18a, 18b, as

shown in FIG. 4. A pressure switch 11 is comprised of a composite 4 and electrodes 6, 7 as shown in FIG. 3 or a composite 4 and pressure plates 18a, 18b as shown in FIG. 4.

The composite 4 functionally completes the current path between first electrode 6 and second electrode 7 during acceptable operating conditions and interrupts current flow when a fault condition occurs. The composite 4 is either conductive or resistive based on the pressure state within the composite 4. For example, the composite 4 may be conductive above and nonconductive below a threshold pressure. Alternately, the resistivity of the composite 4 may vary with pressure over a range of resistance values.

A typical composite 4 is a pressure dependent conductive material, for example a piezoresistive formulation, comprised of a nonconductive matrix 3 and a conductive filler 2, as schematically shown in FIG. 1. Preferred mixtures have a volume fraction below the percolation threshold wherein conductive filler 2 is randomly dispersed within the nonconductive matrix 3. During compression, the nonconductive matrix 3 between conductive filler 2 particles is dimensional reduced thereby crossing the percolation threshold.

The nonconductive matrix 3 is a resistive, yet compressible material including but not limited to polymers and elastomers. Specific examples include polyethylene, polystyrene, polyvinyldifluoride, polyimide, epoxy, polytetrafluorethylene, silicon rubber, polyvinylchloride, and combinations thereof. Preferred embodiments are comprised of the elastomer RTV R3145 manufactured by the Dow Corning Company.

The conductive filler 2 is an electrically conductive material including but not limited to metals, metal-based oxides, nitrides, carbides, and borides, and carbon black.

Preferred fillers resist deformation under compressive loads and have a melt temperature sufficiently above the thermal conditions generated during current interrupt. Specific metal examples include aluminum, gold, silver, nickel, copper, platinum, tungsten, tantalum, iron, molybdenum, hafnium, combinations and alloys thereof. Other example fillers include $Sr(Fe,Mo)O_3$, $(La,Ca)MnO_3$, $Ba(Pb,Bi)O_3$, vanadium oxide, antimony doped tin oxide, iron oxide, titanium diboride, titanium carbide, titanium nitride, tungsten carbide, and zirconium diboride.

FIG. 2 describes a fabrication method for various composites 4. Generally, composites 4 are prepared from high-purity feedstock, mixed, formed into a solid, and suffused with oil. One or more plates are adhered to the composite 4.

Feedstocks include both powders and liquids. Conductive filler 2 feedstock is typically composed of a fine, uniform powder, one example being 325 mesh titanium carbide. Nonconductive matrix 3 feedstock may include either a fine, uniform powder or a liquid with sufficiently low-viscosity to achieve adequate dispersion of powder. Powder-based formulations are mechanically mixed and compression molded using conventional methods. Polytetrafluorethylene formulations may require sintering within an oven to achieve a structurally durable solid. Powder-liquid formulations, one example being titanium carbide and a silicone-based elastomer, are vulcanized and hardened within a die under low uniaxial loading at room temperature.

The solid composite 4 is placed within a liquid bath thereby allowing infiltration of the additive into the solid. Additives are typically inorganic oils, preferably silicone-based. The composite 4 is exposed to the additive bath to insure complete

suffusion of the solid, whereby exposure time is determined by dimensions and composition of the composite 4. For example, a 0.125-inch by 0.200-inch by 0.940-inch composite 4 composed of titanium carbide having a volume fraction of 66 percent and RTV R3145 having a volume fraction of 34 percent was suffused over a 48 hour period.

Conductive or nonconductive plates are adhered to the composite 4 either before or after suffusion. If prior to suffusion, plates are placed within the die along with the liquid state composite 4. For example, a silicone elastomer composite 4 is adequately bonded to two 0.020-inch thick brass plates by curing at room temperature typically between 3 to 24 hours or at an elevated temperature between 60 to 120 degrees Celcius for 2 to 10 hours. If after suffusion, silicone adhesive is applied between plate and composite 4 and thereafter mechanically pressed to allow for proper bond formation.

A porous, nonconductive matrix 3 improves compression and cooling characteristics of the composite 4 without degrading electrical properties. A porous structure is formed by mechanical methods, one example including drilling, after fabrication of the solid composite 4. Another method includes the introduction of pores during mixing of a powder-based conductive filler 2 with a liquid-based nonconductive matrix 3. An additional method includes the introduction of pores during compression forming the composite 4. Also, pores are formed by heating the composite 4 within an oven resulting in localized heating or phase transitions that result in void formation and growth. Furthermore, highly compressible microspheres composed of a low-density, high-temperature foam may be introduced during mixing. Pores are either randomly oriented or arranged in a repeating pattern. Pore shapes include but are not limited to spheres,

cylinders, and various irregular shapes. A single pore may completely traverse the thickness of a composite 4.

FIGS. 8-9 show an embodiment wherein a plurality of holes 40 traverse the cross section of a pressure switch 11. FIG. 10 shows an embodiment wherein holes traverse the composite 4 within the pressure switch 11.

FIG. 11 shows a further embodiment wherein holes 40 are filled with a temperature sensitive material 41, examples including rods or springs composed of a shape memory alloy. Functionally, the temperature sensitive material 41 is typically a rubbery material below, see FIG. 11a, and hard above, see FIG. 11b, a phase transition temperature. More importantly, the temperature sensitive material 41 produces a large force above a transition temperature designed within the material as readily understood within the art. This force is sufficiently capable of moving the pressure plates 18 or electrodes 6,7 apart and interrupting current flow. The temperature sensitive material 41 is self restoring thereby facilitating current flow after the surrounding composite 4 has cooled.

FIGS. 12-13 show two embodiments wherein at least two temperature sensitive actuators 51 apply a compressive force 22 onto a composite 4 thereby allowing current flow. In FIG. 12, current flows directly through the temperature sensitive actuators 51a, 51b, preferably a shaped memory alloy. When a fault occurs the temperature sensitive actuators 51a, 51b are heated and contract thereby decompressing the composite 4 and interrupting current. The composite 4 is compressed as the temperature sensitive actuator 51 cools. In FIG. 13, current flows through the first

electrode 6 and the second electrode 7 when temperature sensitive actuators 51a, 51b are heated by thermal elements 56a, 56b. Thermal elements 56a, 56b are deactivated when a fault condition occurs thereby decreasing the length of the temperature sensitive actuators 51a, 51b and reactivated after the fault condition is corrected thereby increasing the length of the temperature sensitive actuators 51a, 51b causing compression of the composite 4 and current flow.

FIGS. 5-6 show additional embodiments of the present invention comprised of four pressure switches 11a, 11b, 11c, 11d, a first electrode 6, a second electrode 7, two planar conductors 31a, 31b, four insulators 32a, 32b, 33a, 33b, a restoration element 30, and a pair of actuators 19a, 19b.

Pressure switches 11a, 11b, 11c, 11d are composed of a pressure conduction composite 4 disposed between and adhered to two electrically conducting plates, as described above. A pair of pressure switches 11 are electrically aligned in a serial arrangement about a single electrode, either the first electrode 6 or the second electrode 7. One electrically conducting plate from each pressure switch 11 directly contacts the electrode. Two such pressure switch 11 and electrode arrangements are thereafter aligned parallel and disposed between, perpendicular to and contacting a pair of conductors 31a, 31b so that each pressure switch 11 in a serial arrangement contacts a separate conductor 31. Conductors 31 are composed of materials known within the art and should have sufficient strength to resist deformation when a mechanical load is applied. Thereafter, an insulator 32 is placed in contact with and attached or fixed to each conductor 31. A typical insulator 32 is a planar element composed of an electrically nonconducting material with

sufficient strength to resist deformation when a mechanical load is applied.

At least one restoration element 30 is disposed between and parallel to the serial arrangement of pressure switches 11 and electrodes 6 or 7. The restoration element 30 is attached to separate electrically nonconductive insulators 33a, 33b. Thereafter, insulators 33a, 33b are mechanically attached to, perpendicularly disposed and between the conductors 31a, 31b. Insulators 33a, 33b electrically isolate the restoration element 30 from conductors 31a, 31b. The restoration element 30 decompresses the composite 4 within each pressure switch 11, returning it to its original thickness, when the compressive mechanical load is removed from the insulators 32a, 32b. A restoration element 30 may be a mechanical spring or coil, a pneumatic device, or any similar device that provides both extension and contraction.

In preferred embodiments, an actuator 19 contacts an insulator 32. In one embodiment, at least one actuator 19 is attached or fixed to each insulator 32 opposite of said conductor 31, as shown in FIG. 5. A pair of actively opposed yet equal actuators 19a, 19b apply a mechanical load by pushing onto electrically nonconductive insulators 32a, 32b to compress the composite 4 within each pressure switch 11a, 11b, 11c, 11d, as shown in FIG. 5b. In another embodiment, at least two actuators 19a, 19b are mechanically attached or fixed to a pair of insulators 32a, 32b, see FIG. 6. Again, a pair of actively opposed yet equal actuators 19a, 19b apply a mechanical load by pulling on electrically nonconductive insulators 32a, 32b to compress the composite 4 within each pressure switch 11a, 11b, 11c, 11d, as shown in FIG. 6b.

Variations to the described embodiments also include at least two or more

actively opposed actuators 19 mechanically compressing one or more current controllers 1. FIG. 7 describes a three-by-three arrangement of nine current controllers 1, however not limited to this arrangement. In such embodiments, current controllers 1 are electrically connected parallel thereby providing a total power handling capability equal to the sum of the power handling of individual units.

One or more actuators 19 may be employed to drive two or more current controllers 1. For example, a single actuator 19 or two actively opposed yet equal actuators 19 may apply a mechanically compressive load onto the current controllers 1 so that all are simultaneously compressed and decompressed. Alternatively, one or a pair of actuators 19 may apply a mechanically compressive load onto each individual current controller 1. In this embodiment, it is possible to simultaneously drive all current controllers 1 or to selectively drive a number of units.

The embodiments described above may also include a current measuring device electrically coupled before or after the current controller 1. This device provides real-time sampling of current conditions which are thereafter communicated to the actuators 19. Such monitoring devices are known within the art.

An actuator 19 is a rigid beam-like element composed of an active material capable of dimensional variations when electrically activated. For example, the actuator 19 may extend, contract, or extend and contract, as schematically represented by arrows in FIGS. 5-6. Extension of the actuator 19 increases the overall length of the actuator 19. Actuators 19 are composed of electrically activated devices including piezoelectric, piezoceramic, electrostrictive, magnetostrictive, and shape memory alloy materials. For

example, piezoelectric and piezoceramic materials may be arranged in a planar stack along the actuator 19. Shape memory alloys are mechanically distorted by heating via electrical conduction or heat conduction from an adjacent body, one example including the composite 4 during fault condition. Alternatively, an actuator 19 may be a commercially available high-speed piezo-controlled pneumatic element comprised of a pneumatic diaphragm with pilot operated high-bypass value.

The description above indicates that a great degree of flexibility is offered in terms of the present invention. Although embodiments have been described in considerable detail with reference to certain preferred versions thereof, other versions are possible. Therefore, the spirit and scope of the appended claims should not be limited to the description of the preferred versions contained herein.